



## Machining of Austenite Steels Using the Method of Preliminary Local Cryogenic Treatment

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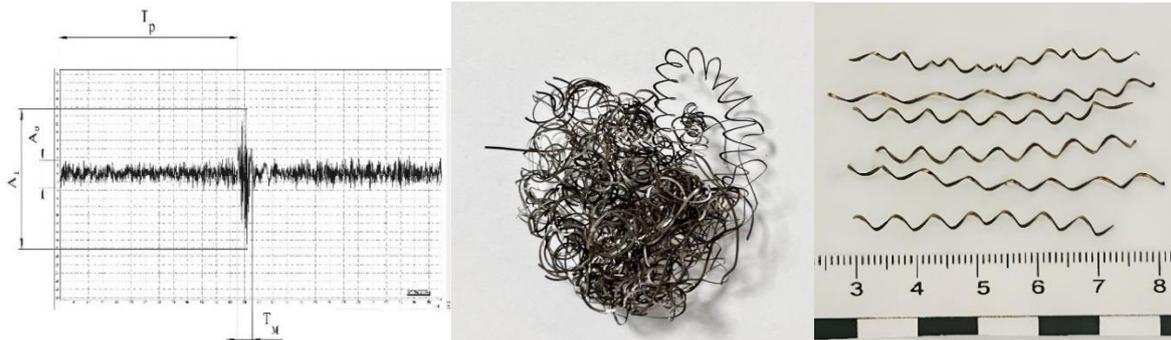
Auto Oscillations

### ABSTRACT

The oil and gas industry uses austenite stainless steels because of their high strength, flexibility, and resistance to the impacts of the atmosphere, damp environment, acids, salts, and other harsh chemicals. Problems in machining of such steels are associated with the formation of drain chip, their adhesion to the edge of the tool with the formation of build-up and the emergence of vibrations, which complicates the machining process and reduces its quality. The complexity of machining places greater demands on the tool used, the rigidity of technological equipment mandates the use of coolant, and various ways of chip removal. The scientific novelty consists in the fact that development of a method matches local cryogenic treatment with mechanical processing, ensuring automatic chip breaking and increased productivity. The influence of the method of cryogenic treatment on the structure, properties and machinability of austenitic steels was evaluated on the most common steel grade 08Kh18N10T. The formation of a magnetic martensitic phase with increased hardness at the boundaries of austenitic grains, which causes a change in the mechanism and conditions of chip formation in the local zone, acts as a stress concentrator, resulting in drain chip segmentation and improved machinability. The main findings include an analysis of the method's impact on the dynamic stability of the mechanical processing technological system; reduction of surface roughness by 2 times during mechanical processing with local cryogenic treatment compared to conventional cutting; ensuring stable segmentation and uniform fragmentation of the chip.

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### Graphical Abstract



### 1. INTRODUCTION

Oil is an important strategic resource for the world economy not only because of its role in providing energy,

but also because of its extensive use in chemical and other industrial sectors (1-3). Countries with large oil reserves, such as Saudi Arabia, Iran, Russia and the United States, not only influence the global energy

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market, but also have significant geopolitical influence by regulating oil production and exports, strongly influencing national policies and strategies. Although many countries are seeking to reduce their dependence on oil and switch to renewable energy sources, oil and natural gas will continue to play an important role in the coming decades, remaining indispensable energy sources in modern life (4).

Therefore, the oil and gas industry plays a key role in providing vital national energy security and defense capabilities, generates large foreign exchange earnings from exports, and makes an important contribution to national budgets. In addition, this industry also creates millions of jobs and contributes to the development of infrastructure and new technologies. The oil and gas industry is an important sector of the economy specializing in the extraction, processing and distribution of oil and natural gas products.

Stainless steels with special corrosion resistance and high strength are widely used in the oil and gas industry (5, 6). The main group of stainless steels, most widely used in industry, is formed by corrosion-resistant austenitic chromium-nickel steels. Typical austenitic stainless steels in addition to iron contain chromium from 16 to 20% and nickel from 9 to 12%, and are known in world practice as steels of type 18-10. Chromium provides the ability of steel to passivate and makes it resistant to aggressive environments, and nickel stabilizes the  $\gamma$ -phase (austenite) in iron, in which the steel is at room temperature, and transforms it into the austenite class. Additionally, steel may contain small amounts of such elements as manganese, silicon and molybdenum (7, 8). In the world practice austenitic stainless steels have unique service properties, are able to retain their mechanical properties at low temperatures, which makes them suitable for use in extreme climatic conditions of Arctic regions and deep sea, as cryogenic materials (9). High stability of characteristics and durability, including at elevated temperatures due to the preservation of the austenitic phase and low tendency to grain growth, allows the steel to be used also for the production of heat-resilient and heat-resistant equipment, in the chemical industry (10-12).

However, machining of austenitic stainless steels faces many difficulties due to high ductility and viscosity of the steel, its tendency to harden during deformation and the formation of drain chip (13). Due to the low thermal conductivity of austenitic steels, there is also an increase in temperature in the cutting zone, which is accompanied by increased adhesion of steel to the tool, its adhesion to the cutting wedge and the occurrence of uneven vibrations (14-16). All this leads to high loads (cutting forces) and accelerated wear and destruction of the tool, as well as to the deterioration of the quality of the surface layer of parts. To eliminate these disadvantages it is necessary to reduce the cutting speed,

which leads to a decrease in the productivity of the process. Poor machinability of austenitic stainless steels imposes higher requirements on the used tools and rigidity of the equipment, causes the need to use coolant and chip breaking (17, 18).

At present, a number of methods of machining of difficult-to-machine materials, including austenitic class steels, developed by domestic and foreign researchers are used in research and production practice. Among them can be mentioned machining with vibrations, laser machining, machining with the use of coolants, etc. Each of these methods has both its advantages and limitations. However, so far no universal method has been developed that allows to completely eliminate technological problems arising in the machining of austenitic steels and provides an optimal combination of productivity, quality and economic efficiency (19, 20).

One of the methods used to increase the efficiency of mechanical processing of products from austenitic stainless steels is the method of local cryogenic treatment on their surface during processing. The essence of the method lies in the fact that during thermal exposure of austenitic steel with liquid nitrogen temperature (-196 °C) in the zone of exposure due to a sharp temperature gradient, steel properties change, including phase and structural transition from  $\gamma$ -austenite to  $\alpha$ -martensite (21-23), which leads to the formation of structural heterogeneity and increase in micro-hardness in the zone of exposure. During subsequent machining, such areas serve as stress concentrators that ensure chip breaking and reduce the cutting force during machining (24-26).

Based on the above analysis, a method of machining of parts made of austenitic steels by means of preliminary local exposure to ultra-low temperatures was developed and applied in order to ensure automatic chip breaking and elimination of build-up. The advantages of the method of machining on the basis of local cryogenic treatment with automatic chip breaking are the following: reduction of cutting force and friction, increase of cutting tool life, increase of efficiency and quality of machining.

## 2. METHODOLOGY AND EXPERIMENTAL PART

The essence of the method of mechanical processing of parts of the type "bodies of rotation" with chip breaking on the basis of preliminary cryogenic treatment is that before machining by cutting is carried out application of liquid nitrogen on the machined surface of the workpiece in the form of a straight line, the impact of which leads to changes in the structure and properties of the surface layer (27, 28). The subsequent process of machining by cutting the workpiece is accompanied by periodic intersection of the cutting plane with the created local zone with a high stress-strain state, which provides segmentation of the drained chip, removal of build-up,

which leads to a decrease in the magnitude of self-oscillations of the technological system and a decrease in the roughness values of the machined surfaces of the obtained item (29-31).

To evaluate the effect of the method of cryogenic treatment on the structure and properties of austenitic steels, experiments were conducted on the basis of 08Kh18N10T steel. The experiments were conducted in such a way that the samples of 08Kh18N10T steel were completely immersed for a time starting from 10 s and up to 180 s in a wide-mouth Dewar vessel with liquid nitrogen one by one so that they did not touch each other and did not create an additional layer of vapor jacket. The results of the experiments are presented below:

- 10 s (sample 1) - active boiling of nitrogen is observed, quenching occurs only on the surface and is accompanied by intensive heat dissipation from the central layers; apparently the transformation has not yet started, as the nitrogen boils vigorously even with intensive twisting of the sample to break the steam jacket, the steam creates a thermal shell and does not let the cold to the metal
- 30 s (sample 2) - nitrogen is still boiling vigorously even with vigorous twitching of the sample to break the vapor jacket, but gradually after about 20 s (the process was monitored with a stopwatch), the boiling starts to subside - the metal cools down and a shear, in all probability martensitic process, starts from the surface to the depth
- 60 s (sample 3) - boiling stopped for about  $\approx$  43 s, the metal cooled down completely - sheared in the volume, all potential martensite was formed and the process stopped
- 180 s (sample 4) - nothing changes compared to 60 s.

Thus, the entire observed transformation process took place within 30 s to 60 s. During such a time interval, only shear martensitic process takes place. Since we are interested in the process of cryogenic treatment on the surface, quenching of the surface in the interval of 30...40 s is sufficient. The formation of martensitic phase, which is magnetic in contrast to austenite, can be confirmed by changes in the magnetic permeability and hardness of the samples.

The study of the magnetic permeability was carried out with a portable magnetometer Magnetoscop 1.070 from FOERSTER. The Magnetoscop 1.070 is a microprocessor-controlled portable magnetometer system with probes for rapid measurement of magnetic flux density as an absolute or differential value (gradient), which is used among others for quality control of stainless steel and confirmation of structural transformations by comparative change of relative magnetic permeability.

The magnetic permeability was measured using a PP-2-5 probe in accordance with ASTM A342/A342M

method 4 (measuring within  $\mu$  from 1.00000 to 2.00000), where  $\mu$  is the magnetic permeability. Standard sample (instrument calibration  $\mu = 1.05$ ).

Magnetic permeability is determined by the formula:

$$\mu = 1 + 4\pi\chi \quad (1)$$

where  $\pi = 3,14$ ;  $\chi$  – magnetic susceptibility - what we actually measure;  $\rho$  – density.

Measurements were made at 4 positions - at opposing points on the diameter. Magnetic permeability before austenitization was 1.097 (residual stresses, etc.), after austenitization 1.085. The measurement results after quenching are summarized in Table 1.

The hardness was determined using a hardness tester HT-1208. The results are summarized in Table 2.

### 3. RESULTS AND DISCUSSION

Based on the obtained results, the graphs of dependence of magnetic permeability and hardness values on the quenching time were plotted (Figure 1).

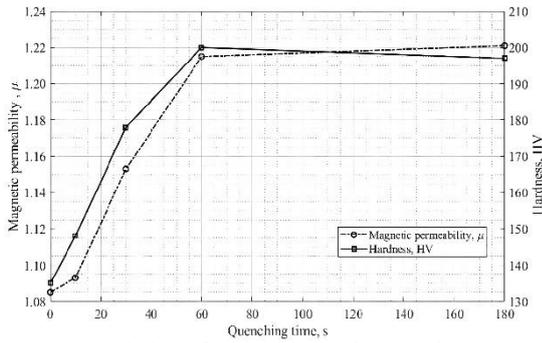
The increase in magnetic permeability and hardness during shock quenching can be related both to the formation of new solid ferromagnetic phases of the martensitic type, most probably  $\alpha$ - or  $\varepsilon$ -martensite, and to the preliminary release of excess phases of the carbide type (32, 33). The rate of their formation is determined

**TABLE 1.** Magnetic permeability values as a function of quenching time

Quenching time t, s	Magnetic permeability, $\mu$				Average magnetic permeability values, $\mu$
	1	2	3	4	
After hardening	1,083	1,085	1,087	1,085	1,085
10	1,088	1,089	1,091	1,093	1,091
30	1,119	1,137	1,141	1,153	1,142
60	1,216	1,214	1,210	1,215	1,214
180	1,218	1,221	1,239	1,221	1,220

**TABLE 2.** Value of microhardness (HV) of austenitic steel at different distance from the surface depending on the quenching time

Quenching time t, s	Distance from the outer surface, mm				
	0	0,5	1	1,5	2
After hardening	135	132	135	139	146
10	148	146	142	153	155
30	178	171	184	183	182
60	200	195	196	201	203
180	197	187	193	195	194



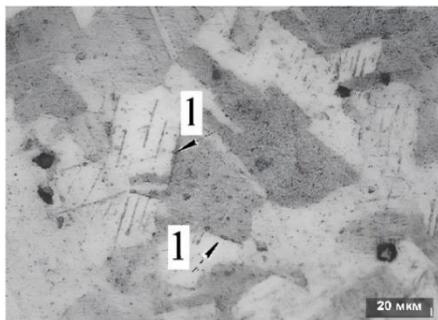
**Figure 1.** Variation of austenitic steel properties (magnetic permeability, hardness) under cryogenic treatment depending on the quenching time

by the rate of metal freezing and corresponds to the shear martensitic mechanism. The amount of martensite, judging by the increase in magnetic permeability, is very small - less than 5% - magnetic susceptibility changes insignificantly, but since the transformation occurs mainly along the boundaries of austenitic grains, and the formed martensite is brittle, a partial change of the breakaway mechanism to spalling is possible even at very low contents, which leads to a change in the conditions of chip in the local area.

The microstructure of 08Kh18N10T steel was investigated on the optical microscope “Zeiss Axio” SN 3835000483. The results of the studies are shown in Figure 2.

Additionally, the effects of plastic deformation on the structure and properties of stainless steel, quenched for 10 and 180 s, were investigated. Pressure was applied using a device with a ball of 5 mm diameter with a force from 0.2 MPa to 1.0 MPa. The sample was cut along the indentation axis with the maximum deformation force using an electrical discharge cutting unit and further fixed with a two-component self-curing epoxy resin.

Micro-hardness was determined using a Reichert-Jung Meaf-3A microscope with a Micro-Duramat 4000E micro-hardness measuring attachment. ThixometPro



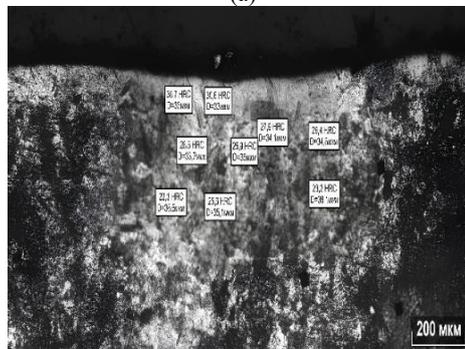
**Figure 2.** Microstructure of 08Kh18N10T steel after cryogenic treatment, where: 1 - martensite along the austenite grain boundaries

program was used for image processing. The results of micro-hardness measurement in the area of the indentation zone are shown in Figure 3.

The hardness in the base material away from the deformation zone is 20.4 HRC, which practically corresponds to the initial hardness of steel after 10 seconds of exposure to nitrogen. In the surface layer under the influence of the ball deformation the hardness increases to 25...25.8 HRC, i.e. by 5.0 units - this is the total increase from deformation and martensitic transformation, however, martensite is not visible in the structure due to its insignificant amount. During deformation of steel after quenching for 60...180 s the hardness in the base is 22.3 HRC, and in the surface layer - from the ball impact - the hardness increased significantly up to 30.6...30.7 HRC. The difference of 8.3...8.4 HRC is the sum of the increase from deformation and martensitic transformation, and the white layer observed in the surface structure is martensite. In the second case, the quenching martensite formed during shock quenching served as a catalyst for the formation of deformation martensite under the same deformation conditions as in the first variant. Similarly, the force impact during cutting causes redistribution of stress-strain states in the stress concentration zones caused by the formation of martensite component at grain boundaries during shock quenching of surface areas, and



(a)



(b)

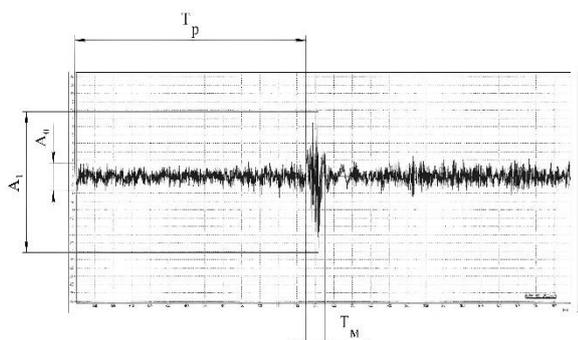
**Figure 3.** Microstructure and micro-hardness of austenitic steel in the zone of deformation by a metal ball after quenching for: a - 10 seconds (x100); b - 60 seconds (x100)

leads to a change in cutting conditions, separation of drain chip into segmented pieces and their removal from the cutting zone (34-36).

Experimental work during machining of 08Kh18N10T steel parts with the use of a two-channel vibration analyzer model VIBXpert EX, provided an opportunity through the measurement of vibration acceleration readings to evaluate the system's auto oscillations, which confirmed the presence of suppression of the oscillatory process during machining of the workpiece on the basis of local cryogenic treatment (33). The result of the experiments are shown in Figure 4.

In the course of experimental studies aimed at measuring vibration accelerations during mechanical processing of parts of the type “bodies of rotation”, it was found that when the tool is introduced into a metastable zone with altered physicomechanical properties, as opposed to the original material, a sharp increase in amplitude  $A_1$  is observed during the time interval  $T_M$ . During the period  $T_M$ , in the processing zone, the build-up of deposits on the cutting edge of the tool is eliminated, and its free movement occurs without material removal. As a result, the system transitions to a stable state with an amplitude of  $A_0$  and a period of  $T_P$ . Based on this, it can be said that the method of local cryogenic treatment has no significant effect on the dynamic stability of the technological system for the mechanical processing of parts of the type “bodies of rotation” made from austenitic steels.

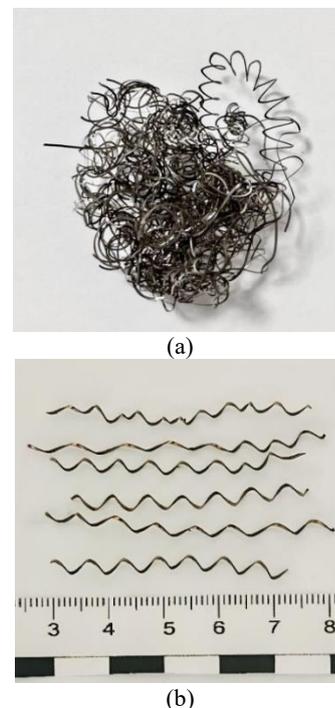
Based on the theory of experimental design for constructing mathematical models that describe the relationship between varying factors and measurable parameters, with the aim of minimizing the number of necessary experiments, it is proposed to apply a central composite design. Technological parameters of the process of machining of parts of the type “bodies of rotation” made from austenitic steels in the course of



**Figure 4.** Vibration accelerations during turning of 08Kh18N10T steel previously subjected to local cryogenic treatment:  $V = 70$  m/min;  $S = 0.12$  mm/rev;  $t = 0.4$  mm;  $n = 750$  min<sup>-1</sup>, where  $T_P$  – machining process in the original material;  $T_M$  – machining process in the hardened zone with martensitic structure along the austenitic grain boundaries

experimental studies were divided into three groups: variable, static and measurable parameters.

The parameters varied during the experiment were: rotational speed  $n$ , min-1; depth of cut  $t$ , mm and feed rate  $S$ , mm/rev. The values of the workpiece speed  $n$  were limited to the values obtained on the lathe model JET GHB 1340A DRO. Static parameters were considered to be those parameters that were not changed during the experimental studies. As a result, it is recommended to apply a method of mechanical processing of parts of the type “bodies of rotation” based on local cryogenic treatment with chip breaking in real production conditions with the following range of technological parameters: local cryogenic treatment time  $t_{LCT} = 30 - 40$  sec.; cutting speed  $n = 750 - 1250$  min<sup>-1</sup>; the cutting depth  $t = 0.15 - 0.5$  mm; feed  $S = 0.12 - 0.20$  mm/rev. These include: dimensional values of the workpieces to be machined and the geometry of the cutting tool. The measured parameters were the roughness of the machined surface  $R_a$ , which was determined on a SurfTest SJ-210 profilometer. The conducted studies showed that with the conventional cutting method (without local cryogenic treatment), the surface roughness value  $R_a$  is  $3.082$   $\mu\text{m}$ , while with mechanical machining by cutting based on local cryogenic treatment, the roughness is reduced by more than 2 times to a value of  $R_a = 1.400$   $\mu\text{m}$ . Visual results of experiments on the segmentation and fragmentation of the cutting chip are presented in Figure 5.



**Figure 5.** Experimental results: a – chip formed during cutting without local cryogenic treatment; b – chip formed during cutting with local cryogenic treatment

The results of the research showed that in a wide range of variation of varying parameters there is a two-fold decrease in surface roughness when using local cooling, which is due to the reduction of vibration activity of the technological system.

#### 4. CONCLUSIONS

1. When compared to other traditional processing methods, an effective solution for machining rotating-type parts made of austenitic stainless steels is the method of local cryogenic treatment, which ensures stable segmentation, automatic chip breaking and removal of burr formation, and also contributes to increased productivity, product quality (surface roughness of the product), and tool life. Despite some challenges in terms of cost and technology, the prospects for applying this method in the manufacturing industry are very promising, especially given the constantly increasing demands for product quality.

2. Under the influence of ultra-low temperatures on the structure of austenitic steels in the zone of local impact on the machined surface of the work piece martensitic transformation occurs, characterized by a different crystal structure compared to austenite and high hardness. Due to the high stability of austenite in stainless steels, the formation of marten site occurs mainly at the boundaries of austenite grains, which creates a metastable structure that has modified mechanical properties compared to the original structure.

3. Significant (or substantial) change in the structure and physical and mechanical properties of austenitic steel parts in the local area of shock quenching leads to periodic changes in the conditions of metal shear by the cutting wedge during subsequent machining and to changes in the cutting conditions, which is accompanied by a decrease in the vibration activity of the technological system, and thus reduces the values of roughness of machined surfaces and improves the quality of the machined surface.

4. It has been established that during the mechanical processing of parts of the type "bodies of rotation" made from austenitic steels based on local cryogenic treatment, the contact time of the work piece in the local area with liquid nitrogen is 30 – 40 sec., which allows achieving a surface roughness of  $R_a = 1.4 \mu\text{m}$ , which is 2 times lower compared to conventional processing methods. The application of the local cryogenic treatment method for the mechanical processing of parts of the type "bodies of rotation" made from austenitic steels ensures stable segmentation of chip into equal segments in the range of 150...200 mm, improves the surface roughness of the finished products in the final operation, and does not significantly affect the dynamic stability of the cutting tool.

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**Persian Abstract**

چکیده

صنعت نفت و گاز به دلیل استحکام بالا، انعطاف‌پذیری و مقاومت در برابر اثرات جو، محیط مرطوب، اسیدها، نمک‌ها و سایر مواد شیمیایی خشن، از فولادهای ضد زنگ آستنیتی استفاده می‌کند. مشکلات ماشینکاری چنین فولادهایی با تشکیل براده‌های تخلیه، چسبندگی آنها به لبه ابزار با تشکیل رسوب و ایجاد ارتعاشات مرتبط است که فرآیند ماشینکاری را پیچیده کرده و کیفیت آن را کاهش می‌دهد. پیچیدگی ماشینکاری، ابزار مورد استفاده را با تقاضای بیشتری مواجه می‌کند، صلیبیت تجهیزات تکنولوژیکی، استفاده از مایع خنک‌کننده و روش‌های مختلف حذف براده را ایجاب می‌کند. نوآوری علمی این روش در این واقعیت نهفته است که توسعه آن، عملیات برودتی موضعی را با پردازش مکانیکی تطبیق می‌دهد و شکستن خودکار تراشه و افزایش بهره‌وری را تضمین می‌کند. تأثیر روش عملیات برودتی بر ساختار، خواص و قابلیت ماشینکاری فولادهای آستنیتی بر روی رایج‌ترین درجه فولاد  $\text{Kh18N10T} \cdot 0.8$  ارزیابی شد. تشکیل فاز مارتنزیتی مغناطیسی با افزایش سختی در مرزهای دانه‌های آستنیتی، که باعث تغییر در مکانیسم و شرایط تشکیل تراشه در منطقه محلی می‌شود، به عنوان یک متمرکزکننده تنش عمل می‌کند و منجر به تقسیم‌بندی تراشه تخلیه و بهبود قابلیت ماشینکاری می‌شود. یافته‌های اصلی شامل تجزیه و تحلیل تأثیر روش بر پایداری دینامیکی سیستم تکنولوژیکی پردازش مکانیکی؛ کاهش زبری سطح به میزان ۲ برابر در طول پردازش مکانیکی با عملیات برودتی موضعی در مقایسه با برش معمولی؛ تضمین تقسیم‌بندی پایدار و تکه‌تکه شدن یکنواخت تراشه است.